Process and apparatus for a wavelength tuning source

de Boer, J.F.; Bouma, B. E.; Yun, S-H; Oh, W. Y.; Tearney, G. J.

2011

US007864822B2

(12) **United States Patent**
Bouma et al.

(10) **Patent No.: US 7,864,822 B2**
(45) **Date of Patent: Jan. 4, 2011**

(54) **PROCESS AND APPARATUS FOR A WAVELENGTH TUNING SOURCE**

(75) Inventors: **Brett Eugene Bouma**, Quincy, MA (US); **Seok-Hyun (Andy) Yun**, Cambridge, MA (US); **Wang-Yuhl (William) Oh**, Cambridge, MA (US); **Johannes F. De Boer**, Amstelveen (NL); **Guillermo J. Tearney**, Cambridge, MA (US)

(73) Assignee: **The General Hospital Corporation**, Boston, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **12/369,556**

(22) Filed: **Feb. 11, 2009**

(65) **Prior Publication Data**

US 2009/0257461 A1 Oct. 15, 2009

Related U.S. Application Data

(62) Division of application No. 11/867,953, filed on Apr. 11, 2008, now Pat. No. 7,724,786, which is a division of application No. 10/861,179, filed on Jun. 4, 2004, now Pat. No. 7,519,096.

(60) Provisional application No. 60/476,600, filed on Jun. 6, 2003, provisional application No. 60/514,769, filed on Oct. 27, 2003.

(51) **Int. Cl.**
H01S 3/10 (2006.01)

(52) **U.S. Cl.** **372/20**; 372/28; 372/32

(58) **Field of Classification Search** 372/20, 372/28

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,639,999	A	2/1987	Daniele
4,763,977	A	8/1988	Kawasaki et al.
4,940,328	A	7/1990	Hartman
4,984,888	A	1/1991	Tobias et al.
5,202,931	A	4/1993	Bacus et al.
5,251,009	A	10/1993	Bruno
5,281,811	A	1/1994	Lewis

(Continued)

FOREIGN PATENT DOCUMENTS

CN	1550203	12/2004
JP	20030035659	2/2003
WO	2005082225	9/2005

OTHER PUBLICATIONS

Office Action dated Jul. 7, 2010 for U.S. Appl. No. 11/624,277.
Montag Ethan D., "Parts of the Eye" online textbook for JIMG 774: Vision & Psycophysics, download on Jun. 23, 2010 from http://www.cis.rit.edu/people/faculty/montag/vandplite/pp./chap_8/ch8p3.html.
Office Action dated Jul. 16, 2010 for U.S. Appl. No. 11/445,990.
Office Action dated Jul. 20, 2010 for U.S. Appl. No. 11/625,135.
Office Action dated Aug. 5, 2010 for U.S. Appl. No. 11/623,852.

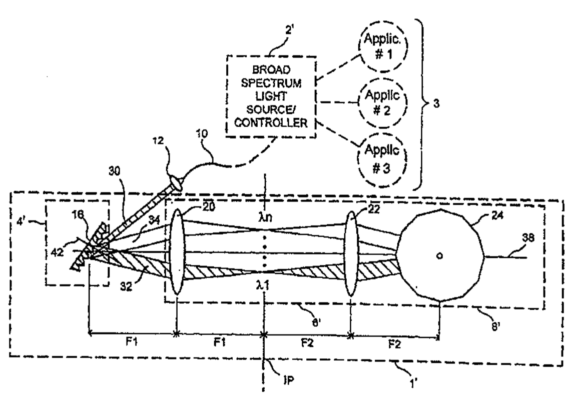
(Continued)

Primary Examiner—Dung T Nguyen
(74) *Attorney, Agent, or Firm*—Dorsey & Whitney LLP

(57) **ABSTRACT**

An apparatus and source arrangement for filtering an electromagnetic radiation can be provided which may include at least one spectral separating arrangement configured to physically separate one or more components of the electromagnetic radiation based on a frequency of the electromagnetic radiation. The apparatus and source arrangement may also have at least one continuously rotating optical arrangement which is configured to receive at least one signal that is associated with the one or more components. Further, the apparatus and source arrangement can include at least one beam selecting arrangement configured to receive the signal.

6 Claims, 16 Drawing Sheets



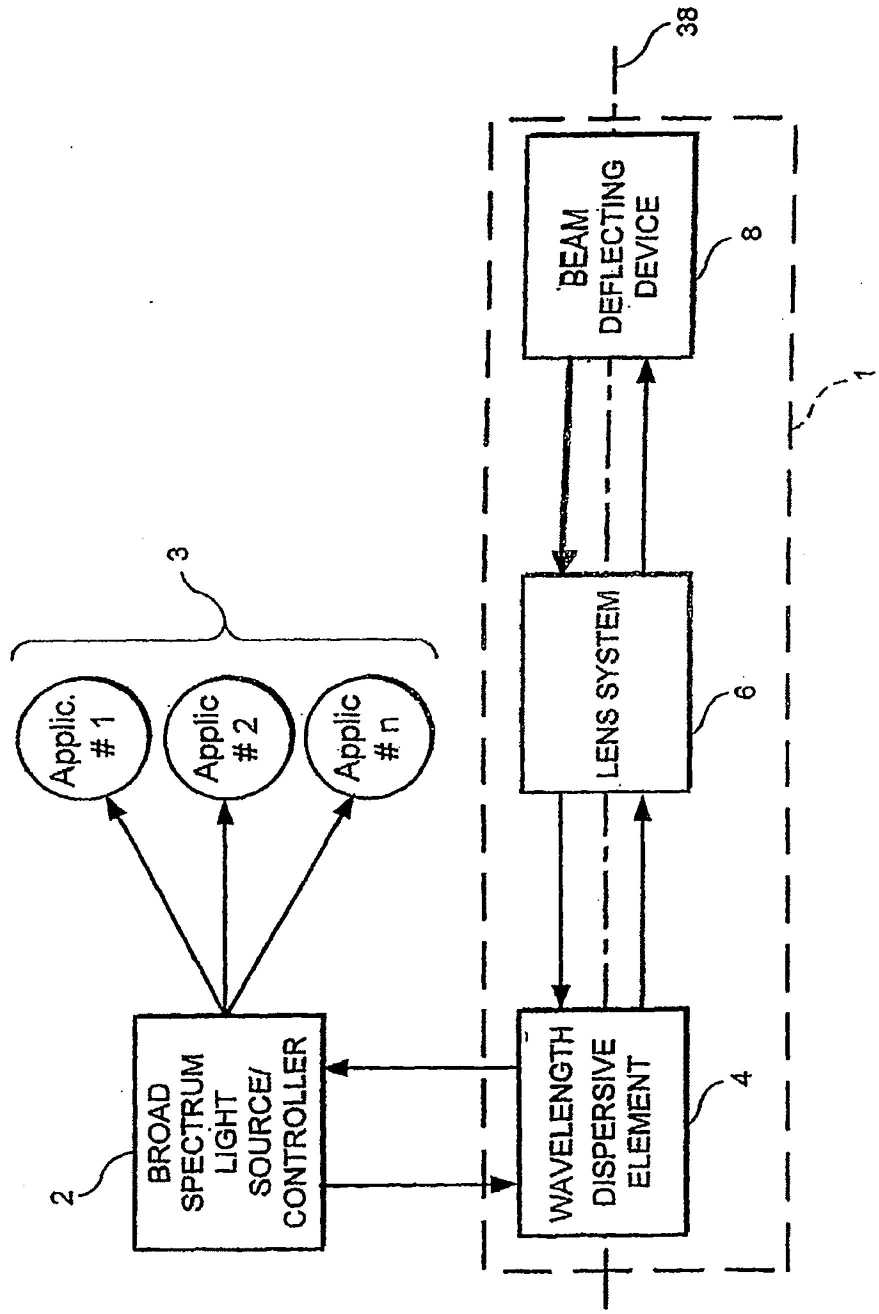

BROAD SPECTRUM LIGHT SOURCE/ CONTROLLER
2
Applic. # 1
Applic # 2
Applic # n
3
WAVELENGTH DISPERSIVE ELEMENT
4
LENS SYSTEM
6
BEAM DEFLECTING DEVICE
8
38
1

FIG. 1A

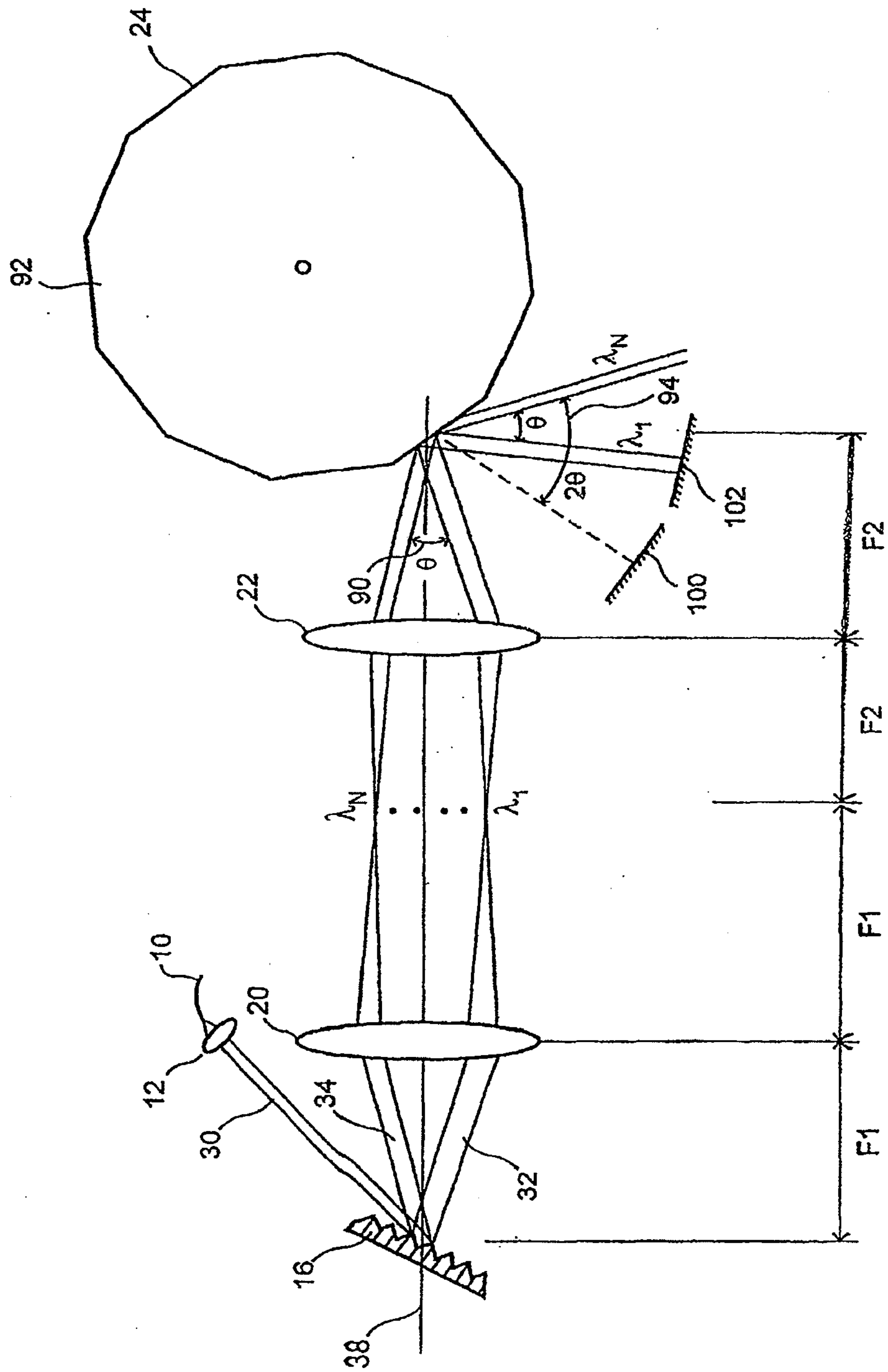
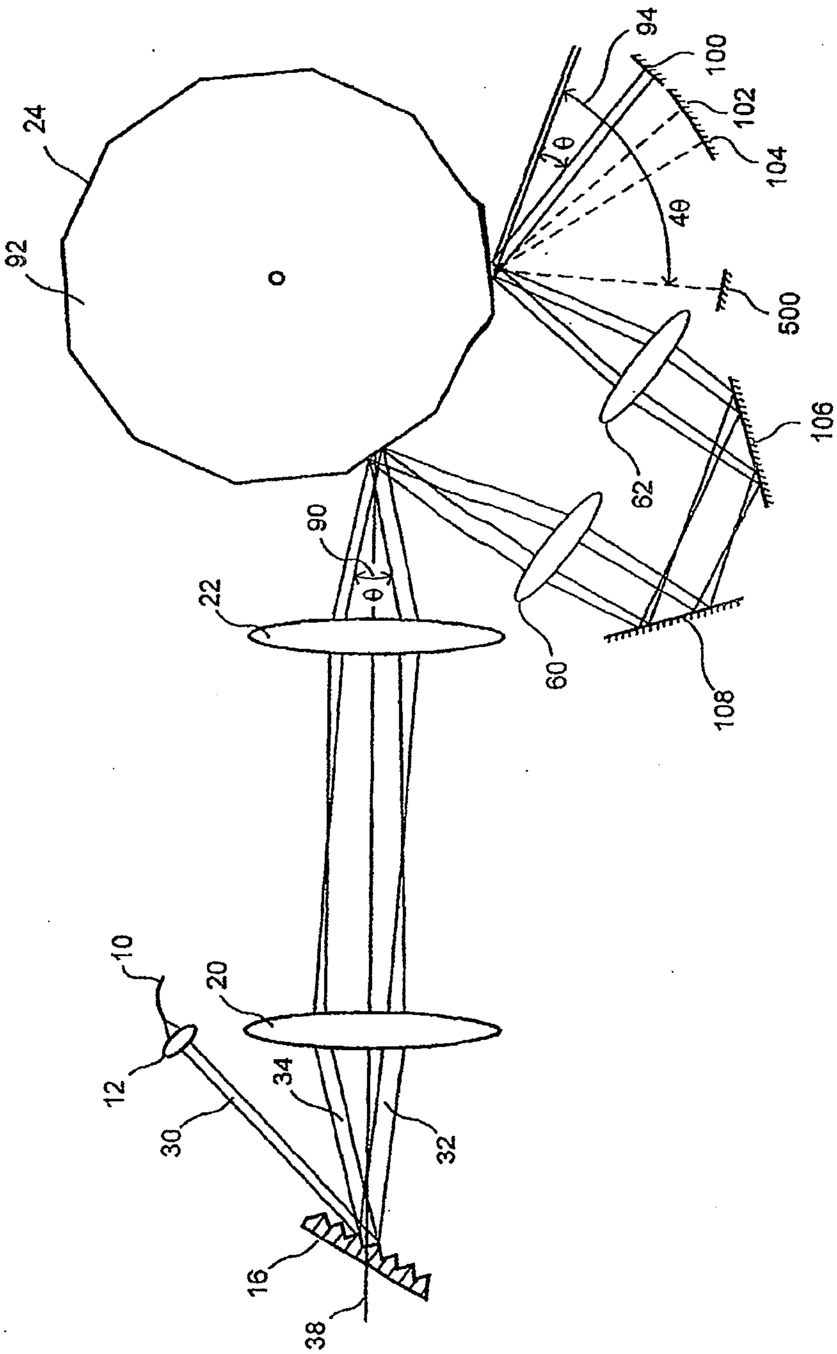

24
92
94
102
100
22
90
10
20
12
30
34
32
16
38
F1
F1
F2
F2
λ_N
λ_1
θ
2θ

FIG. 1C



24
92
94
100
102
104
θ
4θ
500
106
62
60
108
90
θ
22
20
10
12
34
30
32
16
38

FIG. 1E

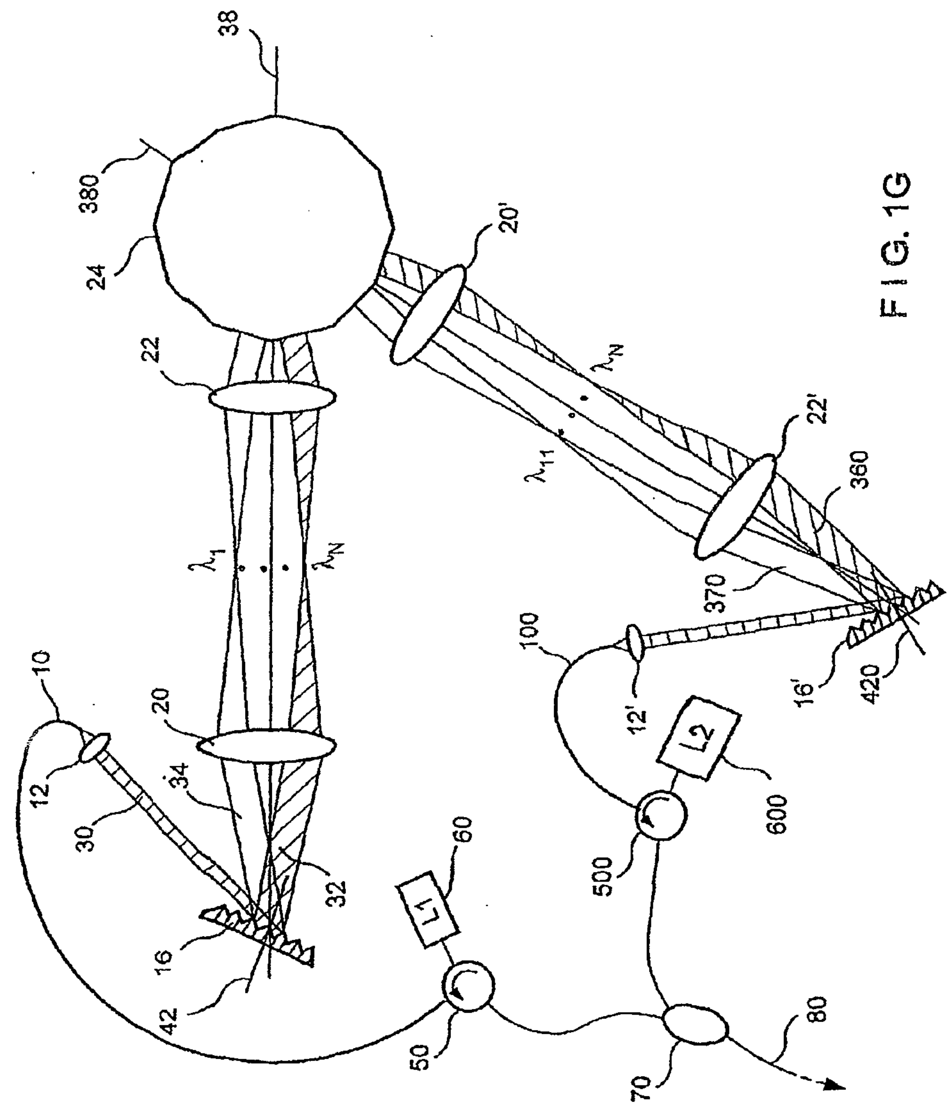
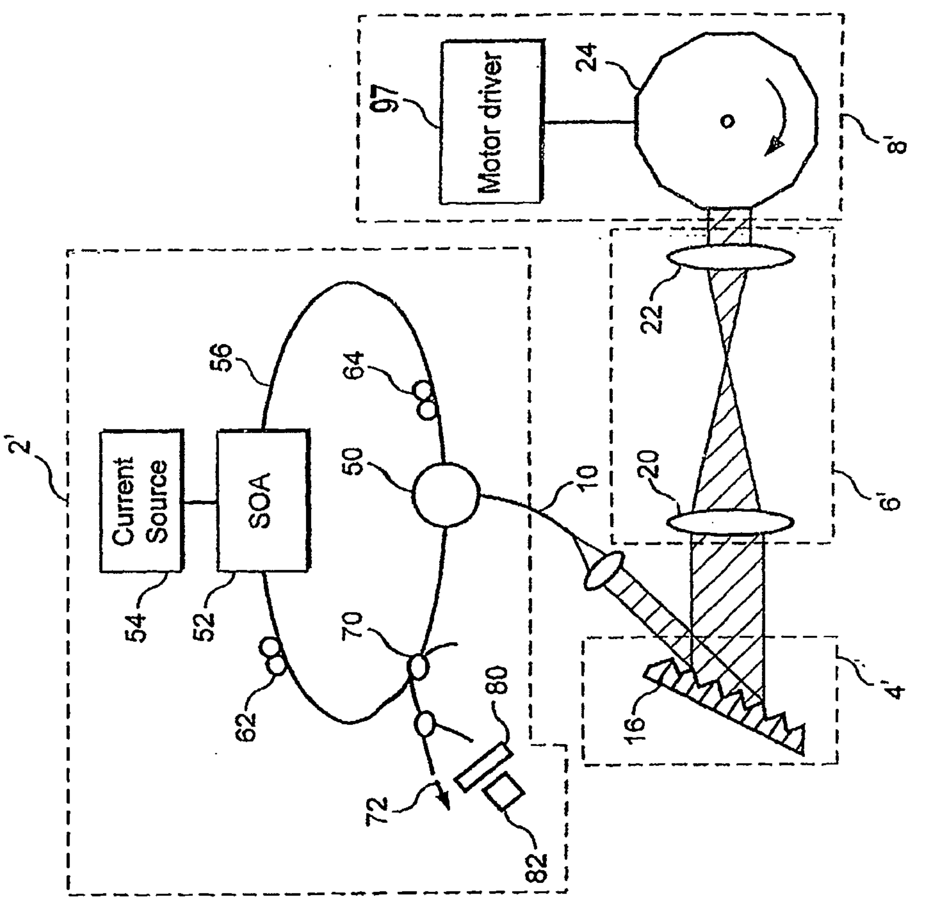

38
380
24
20'
22
22'
λ_N
λ_{11}
360
370
λ_1
λ_N
10
20
100
12
34
30
12'
16'
420
L2
600
L1
60
32
500
16
42
50
70
80

FIG. 1G


Motor driver
97
24
8'
22
20
6'
Current Source
SOA
2'
56
64
50
10
54
52
70
62
80
16
4'
72
82

F I G. 3

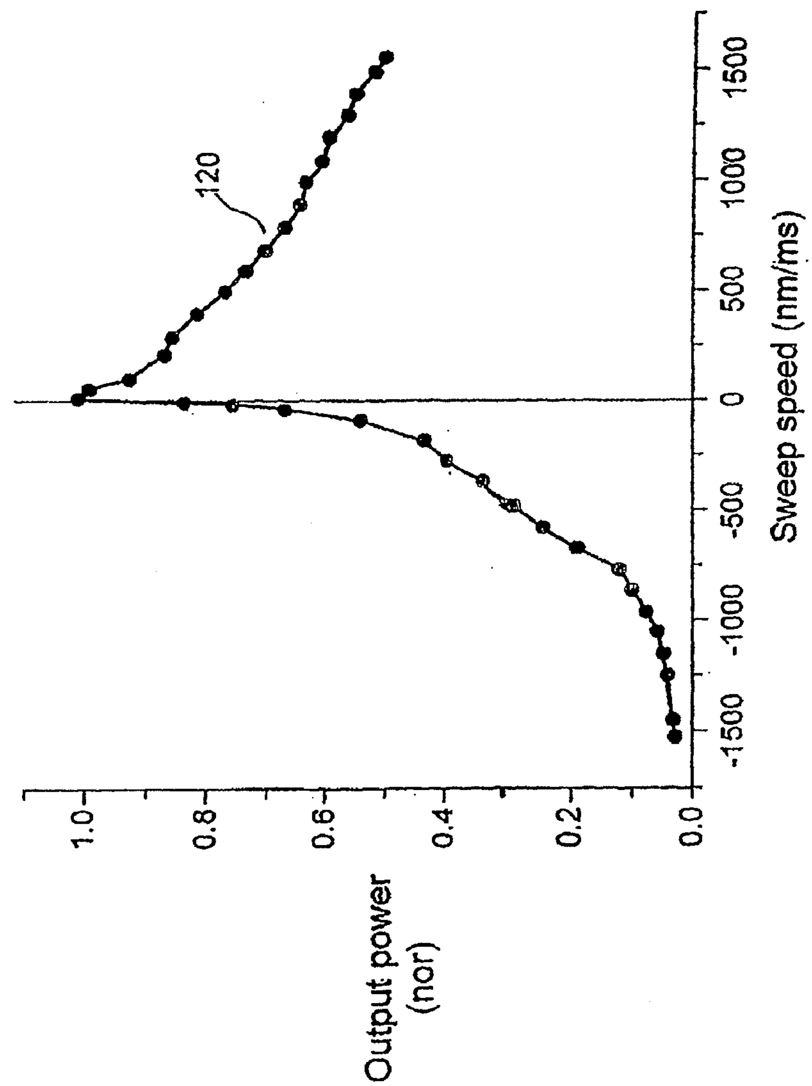

Output power (nor)
1.0
0.8
0.6
0.4
0.2
0.0
-1500
-1000
-500
0
500
1000
1500
Sweep speed (nm/ms)
120

FIG. 5

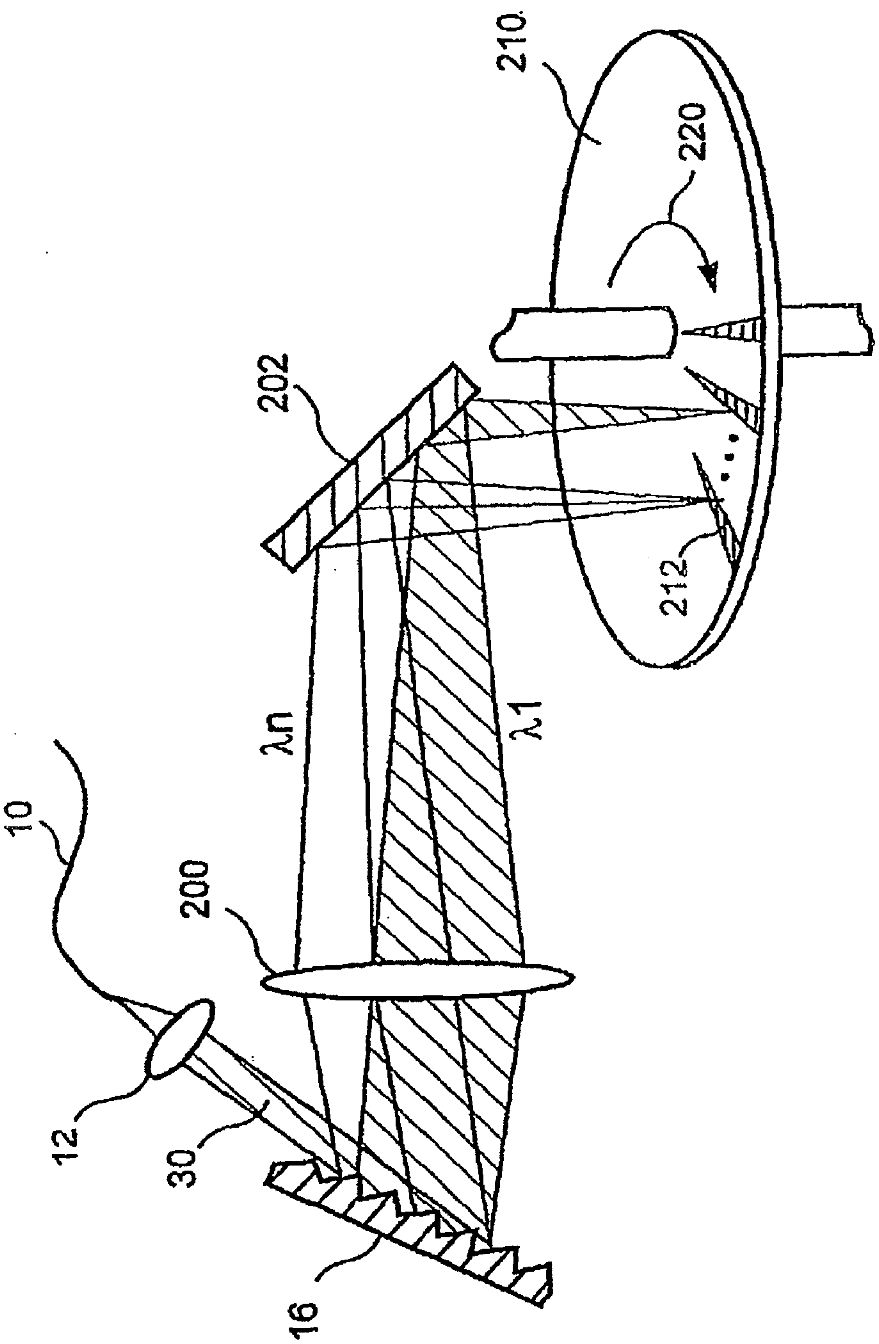


FIG. 7

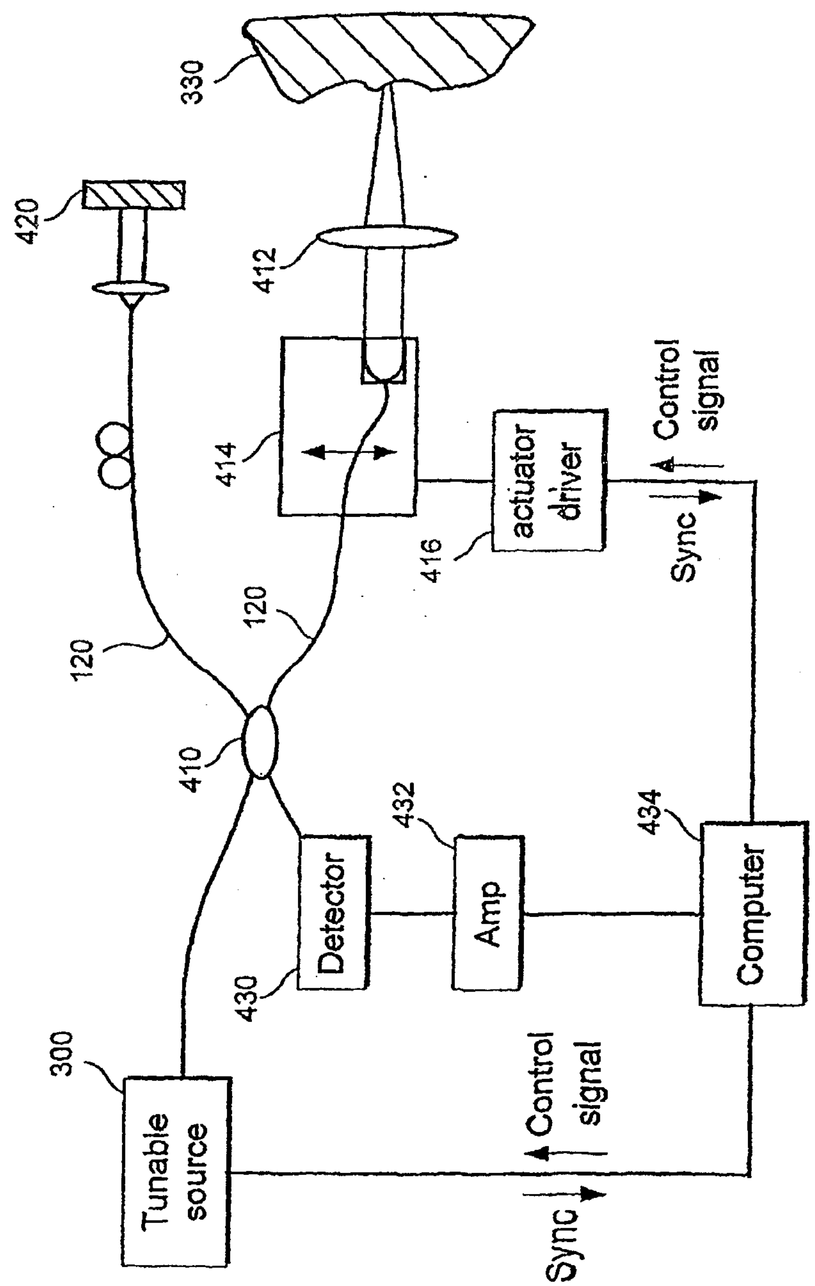

330
420
412
414
416
actuator driver
Control signal
Sync
120
120
410
432
434
Detector
Amp
Computer
430
300
Tunable source
Control signal
Sync

FIG. 9

PROCESS AND APPARATUS FOR A WAVELENGTH TUNING SOURCE

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is a divisional of U.S. patent application Ser. No. 11/867,953 filed Apr. 11, 2008 now U.S. Pat. No. 7,724,786, which is a divisional of U.S. patent application Ser. No. 10/861,179 filed Jun. 4, 2004 now U.S. Pat. No. 7,519,096. This application also claims priority from U.S. Patent Application Ser. No. 60/476,600 filed on Jun. 6, 2003 and U.S. Patent Application Ser. No. 60/514,769 filed on Oct. 27, 2003, the entire disclosures of which is incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates generally to optical systems and more particularly to an optical wavelength filter system for wavelength tuning.

BACKGROUND OF THE INVENTION

Considerable effort has been devoted for developing rapidly and widely tunable wavelength laser sources for optical reflectometry, biomedical imaging, sensor interrogation, and tests and measurements. A narrow line width, wide-range and rapid tuning have been obtained by the use of an intra-cavity narrow band wavelength scanning filter. Mode-hopping-free, single-frequency operation has been demonstrated in an extended-cavity semiconductor laser by using a diffraction grating filter design. Obtaining single-frequency laser operation and ensuring mode-hop-free tuning, however, may use a complicated mechanical apparatus and limit the maximum tuning speed. One of the fastest tuning speeds demonstrated so far has been limited less than 100 nm/s. In certain applications such as biomedical imaging, multiple-longitudinal mode operation, corresponding to an instantaneous line width as large or great than 10 GHz, may be sufficient. Such width may provide a ranging depth of a few millimeters in tissues in optical coherence tomography and a micrometer-level transverse resolution in spectrally-encoded confocal microscopy.

A line width on the order of 10 GHz is readily achievable with the use of an intra-cavity tuning element (such as an acousto-optic filter, Fabry-Perot filter, and galvanometer-driven diffraction grating filter). However, the sweep frequency previously demonstrated has been less than 1 kHz limited by finite tuning speeds of the filters. Higher-speed tuning with a repetition rate greater than 15 kHz may be needed for video-rate (>30 frames/s), high-resolution optical imaging in biomedical applications.

Accordingly, there is a need to overcome the above-described deficiencies.

SUMMARY OF THE INVENTION

According to the exemplary concepts of the present invention, an optical wavelength filter may be provided that can be tuned with a repetition rate of greater than 15 kHz over a wide spectral range. In addition, a wavelength tuning source comprising such optical filter in combination with a laser gain medium may be provided. The tuning source may be useful in video-rate optical imaging applications, such as the optical coherence tomography and spectrally encoded confocal microscope.

In general, the optical filter according to one exemplary embodiment of the present invention may include a diffraction grating, a rotating polygon scanner, and a telescope. Such optical filter can be operated at a tuning speed more than an order of magnitude higher than the conventional filters. The wavelength tunable light source may be implemented by employing the filter, e.g., in combination with a laser gain medium. The filter and gain medium may further, be incorporated into a laser cavity. For example, a laser can emit a narrow band spectrum with its center wavelength being swept over a broad wavelength range at a high repetition rate.

In one exemplary embodiment of the present invention, an apparatus is provided which includes an arrangement for emitting an electromagnetic radiation that has a spectrum whose mean frequency changes substantially continuously over time. Such radiation is may be associated with a tuning speed that is greater than 100 terahertz per millisecond. The mean frequency can change repeatedly at a repetition rate that is greater than 5 kilohertz or over a range greater than 10 terahertz. The spectrum may have a tuning range covering a portion of the visible, near-infrared or infrared wavelengths. Exemplary spectra may be centered at approximately at 850 nm, 1300 nm or 1700 nm wavelengths. Further, the spectrum may have an instantaneous line width that is smaller than 100 gigahertz. The apparatus may also include a laser cavity with a roundtrip length shorter than 5 m. The apparatus may also have a polygon scanner arrangement which may be adapted to receive at least a portion of the emitted electromagnetic radiation and reflect or deflect the portion to a further location. In addition, a beam separating arrangement can be provided which selectively receives components of the electromagnetic radiation.

According to another exemplary embodiment of the present invention the apparatus for filtering an electromagnetic radiation can include at least one spectral separating arrangement configured to physically separate one or more components of the electromagnetic radiation based on a frequency of the electromagnetic radiation. The apparatus may also have at least one continuously rotating optical arrangement that is configured to receive the physically separated components and selectively direct individual components to a beam selecting arrangement.

In one exemplary variation of the present invention, the spectral separating arrangement includes a diffraction grating, a prism, a grism, an acousto-optic beam deflector, a virtual phased array, and/or an arrayed waveguide grating. The continuously rotating optical arrangement may be a polygon mirror, a diffractive element, a substantially opaque disk having an array of substantially transparent regions, and/or a substantially transparent disk having an array of substantially reflective regions. The spectral separating arrangement may also include a holographic grating mounted on a substrate comprising a continuously rotating optical arrangement.

In another exemplary variation of the present invention the beam selecting arrangement may be an optical fiber, an optical waveguide, a pinhole aperture, a combination of a lens with an optical fiber, waveguide or pinhole, and/or a spatial filter. The beam selecting arrangement can include a plurality of beam selecting elements, and the electromagnetic radiation which is transmitted by the plurality of beam selecting elements may be combined. The signal may be reflected multiple times from the continuously rotating optical arrangement before being received by the selecting arrangement.

According to yet another exemplary embodiment of the present invention the apparatus for filtering an electromagnetic radiation may include at least one spectral separating

FIG. 6 is an exemplary embodiment of a free-space extended-cavity semiconductor tunable laser arrangement according to the present invention;

FIG. 7 is an illustration of a seventh exemplary embodiment of the optical wavelength filter according to the present invention;

FIG. 8 is a schematic diagram of an exemplary embodiment of a spectrally-encoded confocal microscope that utilizes the tunable laser source according to the present invention;

FIG. 9 is a schematic diagram of an exemplary embodiment of a frequency-domain optical coherence tomography arrangement that utilizes the tunable laser source according to the present invention;

FIG. 10A is a top view of an eighth exemplary embodiment of the wavelength filter according to the present invention; and

FIG. 10B is a perspective plan view of the wavelength filter shown in FIG. 10A.

DETAILED DESCRIPTION

FIG. 1A shows a block diagram of a first exemplary embodiment of an optical wavelength filter **1** in accordance the present invention. In this first exemplary embodiment, the optical wavelength filter **1** can be used in a variety of different applications, general examples of which are described below. In this example, the filter **1** may be coupled to one or more applications **3** via a light source **2**. It should be understood that in certain exemplary applications, the filter **1** can be used with or connected to an application (e.g., one or more of the applications **3**) via a device other than a light source (e.g. a passive or active optical element). In the first exemplary embodiment shown in FIG. 1A, a broad spectrum light source and/or controller **2** (hereinafter referred to as "light controller"), may be coupled to a wavelength dispersing element **4**. The light controller **2** can be further coupled to one or more of the applications **3** that are adapted to perform one or more tasks with or for, including but not limited to, optical imaging processes and optical imaging systems, laser machining processes and systems, photolithography and photolithographic systems, laser topography systems, telecommunications processes and systems, etc. The wavelength dispersing element **4** can be coupled to a lens system **6**, which is further coupled to a beam deflection device **8**.

The light controller **2** can be one or more of various systems and/or arrangements that are configured to transmit a beam of light having a broad frequency (f) spectrum. In one exemplary embodiment, the beam of light may be a collimated beam of light The beam of light can include a plurality of wavelengths $\lambda \ldots \lambda n$, within the visible light spectrum (e.g., red, blue, green). Similarly, the beam of light provided by the light controller **2** can also include a plurality of wavelengths $\lambda \ldots \lambda n$ that may be defined outside of the visible spectrum (e.g., ultraviolet, near infrared or infrared). In one exemplary embodiment of the present invention, the light controller **2** can include a unidirectional light transmission ring, which shall be described in further detail below in connection with FIG. 3 which shows an exemplary embodiment of a wavelength tuning laser source. Further, in another exemplary embodiment of the present invention, the light controller **2** can include a linear resonator system, which shall be described in further detail below in connection with FIG. 6.

The wavelength dispersing element **4** of the optical wavelength filter **1** can include one or more elements that are specifically adapted to receive the beam of light from the light controller **2**, and to conventionally separate the beam of light into a plurality of wavelengths of light having a number of directions. The wavelength dispersing element **4** is further operative to direct portions of light having different wavelengths in equal angular directions or displacements with respect to an optical axis **38**. In one exemplary embodiment of the present invention, the wavelength dispersing element **4** can include a light dispersion element, which may include but not limited to, a reflection grating, a transmission grating, a prism, a diffraction grating, an acousto-optic diffraction cell or combinations of one or more of these elements.

The lens system **6** of the optical wavelength filter **1** can include one or more optical elements adapted to receive the separated wavelengths of light from the wavelength dispersing element. Light at each wavelength propagates along a path which is at an angle with respect to the optical axis **38**. The angle is determined by the wavelength dispersing element **4**. Furthermore, the lens system **6** is adapted to direct or steer and/or focus the wavelengths of light to a predetermined position located on a beam deflection device **8**.

The beam deflection device **8** can be controlled to receive and selectively redirect one or more discrete wavelengths of light back along the optical axis **38** through the lens system **6** to the wavelength dispersing element **4** and back to the light controller **2**. Thereafter, the light controller **2** can selectively direct the received discrete wavelengths of light to any one or more of the applications. The beam deflecting device **8** can be provided in many different ways. For example, the beam deflecting device **8** can be provided from elements including, but not limited to, a polygonal mirror, a planar mirror disposed on a rotating shaft, a mirror disposed on a galvanometer, or an acousto-optic modulator.

FIG. 1B shows a schematic diagram of a second exemplary embodiment of the optical wavelength filter **1'**. The exemplary optical wavelength filter **1'** can be configured as a reflection-type filter which may have substantially identical input and output ports. An input/output optical fiber **10** and a collimating lens **12** can provide an input from a light controller **2'** (which may be substantially similar to the light controller **2** described above with reference to FIG. 1A) to the optical wavelength filter **1'**. The optical wavelength filter **1'** includes a diffraction grating **16**, optical telescoping elements **6'** (hereinafter referred to as "telescope **6'**" and may possibly be similar to the lens system **6** of FIG. 1A), and a polygon mirror scanner **24**. The telescope **6'** can include two lenses, e.g., first and second lenses **20**, **22** with 4-f configuration.

In the second exemplary embodiment of the optical wavelength filter **1'** shown in FIG. 1B, the telescope **6'** includes the first and second lenses **20**, **22**, which are each substantially centered along the optical axis **38**. The first lens **20** may be located at a first distance from the wavelength dispensing element **4'** (e.g., diffraction grating **16**), which can approximately be equal to the focal length F1 of the first lens **20**. The second lens **22** may be located at a second distance from the first lens **20**, which can be approximately equal to the sum of the focal length F1 of the first lens **20** and the focal length F2 of the second lens **22**. Using such arrangement, the first lens **20** can receive one or more collimated discrete wavelengths of light from the wavelength dispersing element **4'**, and can effectively perform a Fourier Transform on each one of the collimated one or more discrete wavelengths of light to provide one or more approximately equal converging beams that are projected onto an image plane IP.

The image plane IP is preferably located between the first lens **20** and the second lens **22** and at a predetermined distance from the first lens **20**. According to one exemplary variation of the present invention, such predetermined distance may be defined by the focal length F1 of the first lens **20**. After such and to the telescope (e.g., similar to the telescope 6' of FIG. 1B), with the angle θ between each other, twice wavelength scans from λ_1 to λ_N are achieved for the polygon rotation of the one facet-to-facet angle θ.

In FIG. 1D which shows a fourth exemplary embodiment of the present invention, the incident angle 90 difference between λ_1 and λ_N to the polygon arrangement 24 is smaller than polygon facet-to facet angle 92, e.g., ϕ (=θ/K, where K>1). This can be achieved by reducing the grating pitch and increasing the F2/F1 ratio. In this exemplary embodiment, the filter tuning speed may be increased by factor of 2K without increasing either the rotation speed of the polygon arrangement 24 or the number of facets of the polygon arrangement 24.

The filter tuning speed can be further increased by having the beam of light reflected multiple times by the polygon arrangement 24. A fifth exemplary embodiment of the present invention, depicted in FIG. 1E, is an arrangement for increasing the tuning speed by factor of 4K, where K is the ratio of angle 92 to angle 90 (K=θ/ϕ). The beam of light is reflected twice (e.g., four times round trip) by the polygon arrangement 24, so that the sweep angle 94 of the reflected light becomes angle 4θ, and the tuning speed becomes 4K times faster. Such reflection can also be assisted with the reflection of surfaces **100, 102, 104, 106** and **108**. This exemplary embodiment of the filter arrangement can be used to broaden the free spectral range ("FSR") of the filter. For example, if one of the final reflectors **102** in the embodiment shown in FIG. 1E is removed, the FSR of the filter may become twice broader. It is likely that there is no tuning speed enhancement in such case. Similarly, it is possible to retain only one final reflector **100** in FIG. 1E. The FSR in this embodiment can become four times broader.

FIG. **1F** shows a sixth exemplary embodiment of the present invention which provides a polygon tuning filter accommodating two light inputs and outputs. For example, in order to support two or more inputs and outputs of this filter, two or more sets of optical arrangements, each respective set including an input/output fiber **10, 10'**, a collimating lens **12, 12'**, a diffraction grating **16, 16'**, and a telescope, may share the same polygon arrangement **24**. Because the scanning mirror of the polygon arrangement **24** is structurally isotropic about the rotation axis, certain optical arrangements that can deliver the beams of light to the polygon arrangement **24** can be accommodated from any directions. Since both sets of optical arrangement in the embodiment of FIG. **1F** utilize the same polygon scanner, their respective scanning optical transmission spectra are synchronized. It should be understood that the exemplary embodiment of FIG. **1F** can be extended to include multiple (greater than 2) optical arrangements each having its own input and output optical channel.

One exemplary application of the above-described polygon tuning filter according to the sixth embodiment of the present invention may be a wide band wavelength scanning light source. In FIG. **1G** which shows a seventh exemplary embodiment of the present invention, a first broadband light source **60** provides a light signal which may have a wavelength λ_1 to λ_i, and a second broadband light source **600** provides another light signal having a wavelength λ_{i-j} to λ_N. When the two optical arrangements supporting the wavelengths λ_1 to λ_i and the wavelengths λ_{i-j} to λ_N, respectively, are synchronized to output approximately the same wavelength at the same instance, such exemplary arrangement may become a wide band wavelength scanning light source with linear scan rate from λ_1 to λ_N. Since the FSR of the polygon scanning filter can be adjusted to be 200 nm or wider without any optical performance degradation, two or more broadband light sources with different center wavelengths can be combined with this filter to provide linear scanning light source over 200 nm tuning bandwidth. It should be understood that the embodiment of FIG. **1G** can be extended to include multiple (e.g., greater than 2) optical arrangements and multiple (e.g., greater than 2) broadband light sources.

The exemplary embodiment illustrated in FIG. **1G** can also be configured so that the wavelength tuning bands of each optical arrangement and broadband light source are discontinuous. In such a configuration, the tuning bands can be swept in a continuous or discontinuous sequential manner or be swept simultaneously.

FIG. **2** shows an exemplary graph of measured characteristics of the filter according to an exemplary embodiment of the present invention. The normalized reflection spectrum of the filter, e.g., a curve **48**, may be measured by using broadband amplifier spontaneous emission light from a semiconductor optical amplifier (SOA) and an optical spectrum analyzer. The optical spectrum analyzer can obtain or record a normalized throughput (reflected) spectrum in peak-hold mode while the polygon arrangement **24** spins at its maximum speed of 15.7 kHz. The measured tuning range may be 90 nm which is substantially smaller than the theoretical value of 126 nm. It is possible to have a discrepancy which may be due to an aberration of the telescope **6'**, primarily field curvature, associated with relatively large angular divergence of the beam from the grating. Such aberration can be corrected using optimized lens designs well known in the art. A curve **46** shown in FIG. **2** illustrates the throughput spectrum when the polygon arrangement is static at a particular position. The observed free spectral range is 73.5 nm, in agreement with a theoretical calculation. The FWHM bandwidth of curve **46** was measured to be 0.12 nm. The discrepancy between the measured FWHM and the theoretical limit of 0.09 nm is reasonable considering the aberration and imperfection of the optical elements.

FIG. **3** shows an exemplary embodiment of the wavelength tuning laser source according to the present invention. For example, the polygon-based filter can be incorporated into an extended-cavity semiconductor laser via a Faraday circulator **50**. Intra-cavity elements may be connected by single-mode optical fibers **10**. The gain medium may be a semiconductor optical amplifier **52** (e.g., SOA, Philips, CQF 882/e). Laser output **72** may be obtained via the 90% port of a fiber-optic fused coupler **70**. Two polarization controllers **64, 62** can be used to align the polarization states of the intra-cavity light to the axes of maximum efficiency of the grating **16**, and of the maximum gain of the SOA **50**. A current source **54** may provide an injection current to the SOA **50**. The polygon arrangement **24** may be driven and controlled by a motor driver **97**. To generate a sync signal useful for potential applications, approximately 5% of the laser output may be directed to a photodetector **82** through a variable wavelength filter **80** with bandwidth of 0.12 nm. In this exemplary implementation, the center wavelength of the filter was fixed at 1290 nm. The detector signal can generate short pulses when the output wavelength of the laser is swept through the narrow passband of the fixed-wavelength filter. The timing of the sync pulse may be controlled by changing the center wavelength of the filter.

FIG. **4A** shows a graph of exemplary first output characteristics (laser spectrum vs. wavelength) of the laser source according to the present invention, and FIG. **4B** is a graph of exemplary second output characteristics (output power vs. time) of the laser source according to the present invention. Turning to FIG. **4A**, curve **110** represents the output spectrum of the laser measured by the optical spectrum analyzer in down to a narrow waist at a given time. Two dimensional en-face image of the sample is constructed by a signal processor 344. The detector 340 is preferably an avalanche photodiode ("APD") followed by a transimpedance amplifier 342. The reflected power may be received through a Faraday circulator 350 or a fiber-optic coupler.

Another exemplary application of the exemplary embodiments of the present invention is for optical coherence tomography ("OCT") the details of which are described in U.S. Pat. No. 5,956,355, the disclosure of which is incorporated herein by reference in its entirety. In one exemplary configuration, depicted in FIG. 9, an output of a tunable source 300 may be directed to a sample 330 through a fiber-optic coupler 410. An objective lens 412 in the probe may typically provide a focus near the surface or within the sample 330. The reference mirror 420 can be placed in a reference arm 120 at a position where an optical path length between two arms of the Michelson interferometer is substantially matched. Alternatively, the reference path can be configured in a transmissive, non-reflective configuration. The detector 430 may be a PIN photodiode followed by a transimpedance amplifier 432 with finite frequency bandwidth. The detector may preferably incorporate polarization diverse and dual balanced detection. The detector signal can be processed in the processor 434 through a fast Fourier transform to construct the depth image of the sample. The probe may be scanned by an actuator 414 and an actuator driver 416 to allow a 3-dimensional image of the sample to be obtained.

FIGS. 10A and 10B show a top and perspective view of another exemplary embodiment of the wavelength tunable filter according to the present invention. An angularly deflecting optical element 700 of this exemplary embodiment can be a rotating polygon arrangement 24 where the facets of the polygon are on the inner diameter of a hollow cylinder. A dispersing element 702 such as a diffraction grating can be placed at the center of the polygon arrangement 24. Light can be delivered to the grating through an optical fiber and collimated onto the grating so that each frequency component of the light is diffracted through a different angle (Θ). Only one narrow range of frequencies may be substantially orthogonal to one facet of the polygon arrangement 24, and therefore such frequency range may be reflected back to the diffraction grating and collected by the optical fiber 704/706. When the cylinder rotates, a surface normal direction for the illuminated polygon arrangement's facet may align with a new narrow frequency range. By rotating the cylinder, frequency tuning can thereby be achieved. When the cylinder rotation angle becomes large, an adjacent facet of the polygon arrangement 24 can become aligned with the light diffracted from the grating and the filter will repeat another frequency tuning cycle. The free spectral range and finesse can be controlled by appropriate choice of the polygon diameter, number of facets, collimated beam diameter and diffraction grating groove density.

The foregoing merely illustrates the principles of the invention. Various modifications and alterations to the described embodiments will be apparent to those skilled in the art in view of the teachings herein. For example, the invention described herein is usable with the exemplary methods, systems and apparatus described in U.S. Patent Application No. 60/514,769. It will thus be appreciated that those skilled in the art will be able to devise numerous systems, arrangements and methods which, although not explicitly shown or described herein, embody the principles of the invention and are thus within the spirit and scope of the present invention.

What is claimed is:

1. An apparatus comprising:

a first arrangement configured to emit an electromagnetic radiation that has a spectrum whose mean frequency changes at a rate of that is greater than about 100 terahertz per millisecond, and

a second arrangement configured to at least one of transmit or reflect at least one portion of the electromagnetic radiation based on a frequency of the electromagnetic radiation, wherein the at least one portion has a full-width-at-half-maximum frequency distribution that is smaller than about 100 GHz.

2. The apparatus according to claim 1, wherein the second arrangement is situated on or within the first arrangement.

3. The apparatus according to claim 1, wherein the mean frequency changes repeatedly at a repetition rate that is greater than about 5 kilohertz.

4. The apparatus according to claim 3, wherein the mean frequency changes over a range that is greater than about 10 terahertz.

5. The apparatus according to claim 4, wherein the spectrum has an instantaneous line width that is smaller than about 100 gigahertz.

6. The apparatus according to claim 1, further comprising a laser resonating arrangement which forms an optical circuit and which is configured to control a spatial mode of the electromagnetic radiation, wherein the first arrangement causes the electromagnetic radiation to propagate substantially unidirectionally within at least a portion of the resonating arrangement.

* * * * *